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Thinning Impacts on Carbon and Water Budgets in a Temperate Deciduous Forest Ecosystem

Ufuk Özkan, Yusuf Serengil, Erda Çeler, Ferhat Gökbulak, İbrahim Yurtseven, Betül Uygur Erdoğan, Reyhan Sağlam

Abstract

Among various forest management activities, thinning is a prevalent treatment that affects tree growth and living biomass. Increased moisture and light availability may also enhance the mineralization of litter and dead wood organic matter, impacting soil carbon stocks. Thinning may also affect the services forests provide, including water production and nutrient cycling. The impacts of thinning on water yield and carbon stocks have been well documented around the globe while targeting mainly one of these ecosystem services. Our experimental paired catchment study covers both and puts forward long term results. We assessed the carbon stock changes caused by two slight thinning treatments together with the impacts on water yield in experimental paired catchments of 71.9 (W–I) and 77.5 hectares (W–IV) in Istanbul, Türkiye. The null hypothesis was that the slight thinnings did not affect the water yield and carbon stocks significantly. On the carbon stock part, we calibrated and parametrized the CBM–CF3 model with field measurements to simulate changes in carbon stocks of mixed deciduous forest stands. The intensities of the treatments (thinnings) were 11% and 18% of the basal area, performed in 1986 and 2011, respectively. We found that, while C stocks decreased by around 30 tons per hectare during the 1986–2020 period, the water yield was enhanced by approximately 25 mm/yr in the treatment catchment compared to the control watershed during the four-year post-treatment period. This amount of streamflow increase was around 10 percent of the average water yield of the catchments. It was concluded that there was a detectable increase in water yield during the following four years of the slight thinning treatments, while the reduction in abovegound carbon stocks continued for more than three decades.

Keywords: paired catchments, carbon stocks, thinning, water yield

1. Introduction

Thinning is a widespread forestry treatment to maintain forest health and stimulate the growth performances of the stands. Several benefits of thinning have been reported in the literature, such as high-quality timber production, increased carbon sequestration, and enhanced biodiversity (Tsamir et al. 2019, Moreau et al. 2020, Zhou et al. 2020). Additionally, some studies concluded that thinning could increase the resiliency of the ecosystems against forest fires, insect damages, and droughts (Andrade et al. 2020). The influence of thinning on ecosystem functioning has been evaluated and reported extensively. Studies on water use efficiency provided some comparative assessments on carbon removal versus water production. For example, Tsamir et al. (2019) compared the carbon and water fluxes at stand scale and concluded that thinning reduced water use more than carbon uptake. However, there are few studies on a paired catchment methodology that compares the two significant ecosystem functions.

Periodically thinned forests can have higher GHG mitigation benefits than unmanaged forests especially if the harvested timber is used in long-life products (Van Deusen 2010) such as construction materials. Thinning can also enhance the carbon content of the soils. Gong et al. (2021) showed that thinning treatments could increase soil organic carbon contents, especially in dry or low moisture conditions (Gong et al. 2021). Furthermore, managed forests are known for their higher resilience to fires and drought stress (McDowell et al. 2006, Moreno-Gutiérrez et al. 2011, Sohn et al. 2013). In conclusion, the literature overwhelmingly suggests that thinning can increase the resilience of the ecosystems and increase carbon stocks in certain conditions (Kern et al. 2021).

Carbon and water production are generally known as competing ecosystem services. As a general statement, the decrease in stand density also decreases biomass carbon stocks but may enhance water yield through reduced interception and transpiration. However, studies on the hydrologic consequences of thinning mention a threshold cut percentage for a detectable streamflow increase and a period that the increase disappears (Bosch and Hewlett 1982, Serengil et al. 2007).

Paired catchment studies enable robust assessments on the hydrological impacts of forestry treatments. In the methodology, an entire catchment is kept untreated while others are subject to various treatments. In our case, two thinning treatments were assessed. The first one was performed in 1986 and the second one in 2011. The hydrology part of this assessment is based on forty years of continuous flow measurements. A carbon component was added with mass measurements and soil sampling for CBM–CF3 model calibration. Our objective was to evaluate hydrologic responses of the ecosystems together with carbon sequestration performances, especially in the mid and long terms and test if the slight thinnings significantly affect the water yield and carbon stocks in this type of ecosystem and in such conditions.

2. Materials and Methods

2.1 Study Catchments and Treatments

The watershed management department at Istanbul University has initiated a long-term experimental paired catchment study in 1978 in Belgrad Forest (Serengil et al. 2007). Five catchments were allocated and instrumented at the beginning. Later, 2 of the catchments were excluded, and observations went on at the remaining 2, coded as W–I and W–IV. The »control watershed« (W–I) is 71.9 ha, while the »treatment watershed« (W–IV) is 77.5 ha (Fig. 1). The area is situated near the city of Istanbul and is considered an urban forest. Still, the research area is used for producing water and is prohibited from activities.

The paired catchments are covered with old-growth mixed broadleaf stands. The annual precipitation is 1050 mm, and the mean annual temperature is 12.8 °C (Yurtseven et al. 2018). The precipitation falls mainly in winter months followed by fall and spring. This is the typical rainy Black sea climate regime that dominates the northern Black sea shore of the country. There is a dry summer period of 2–3 months that causes moderate water deficit in soils. Despite the dry summer season, the streamflow of the experimental catchments drops to zero only during exceptionally dry years.

The soil type is shallow to deep, gravelly, clay loam in texture, rich in organic matter with moderate permeability rates. Soils are slightly acidic with high erodibility rates. Mull type (quickly decomposing) litter layer is common with an average 5 cm thickness (Özhan 1977, Serengil et al. 2007).

Serengil (2018) defined the study area in the »Balkan mixed forests ecozone« and the climate as »humid, mesothermal oceanic with a moderate soil-water deficit in summer«. The study area is covered with native broadleaf mixed tree species including mainly Oak (*Quercus petraea* L., *Quercus frainetto* Ten.), Beech (*Fagus orientalis* L.), and Hornbeam (*Carpinus betulus* L.) (Balcı et al. 1986, Yurtseven et al. 2018).

Stand type is oak and beech mixture, average stand age is 82 for both species, according to field measurements canopy closure is higher than 70% (dense/very dense), the average basal area is 8.94 (m^2 per ha), average net primary productivity (NPP) is 8.56. Site class was described as side class – III by previous researchers from the area. The average dominant tree height measured during field measurements is 25.18 m.

Paired watersheds were continuously monitored (daliy meteorological parameters for the local wearther station and weekly streamflow measurements) and calibrated with each other for monthly streamflow during the four-year pre-treatment periods. The first selective cutting (thinning) treatment was carried out in W–IV in 1986, involving 11% intervention resulting in 1820 m^3 (8.08 ton C/ha) of timber harvest. The second one (18%) was performed in 2011, accounting for 4867 m^3 (21.61 ton C/ha) timber removal. The harvest residues were left on site, and the timber was produced for industrial use. The harvest and transportation were realized with typical methods of the forest service. No special techniques were used. The selection of the indivduals for removal were based on the tree characteristics and stand structures. The selection of the tree species to be harvested was random but aimed to keep the stand mixture unchanged.

2.2 Paired Catchment Methodology

The paired catchment methodology is a widespread watershed research technique (Balcı et al. 1986, Balcı et al. 1993, Gökbulak et al. 2016, Özhan et al. 2010,

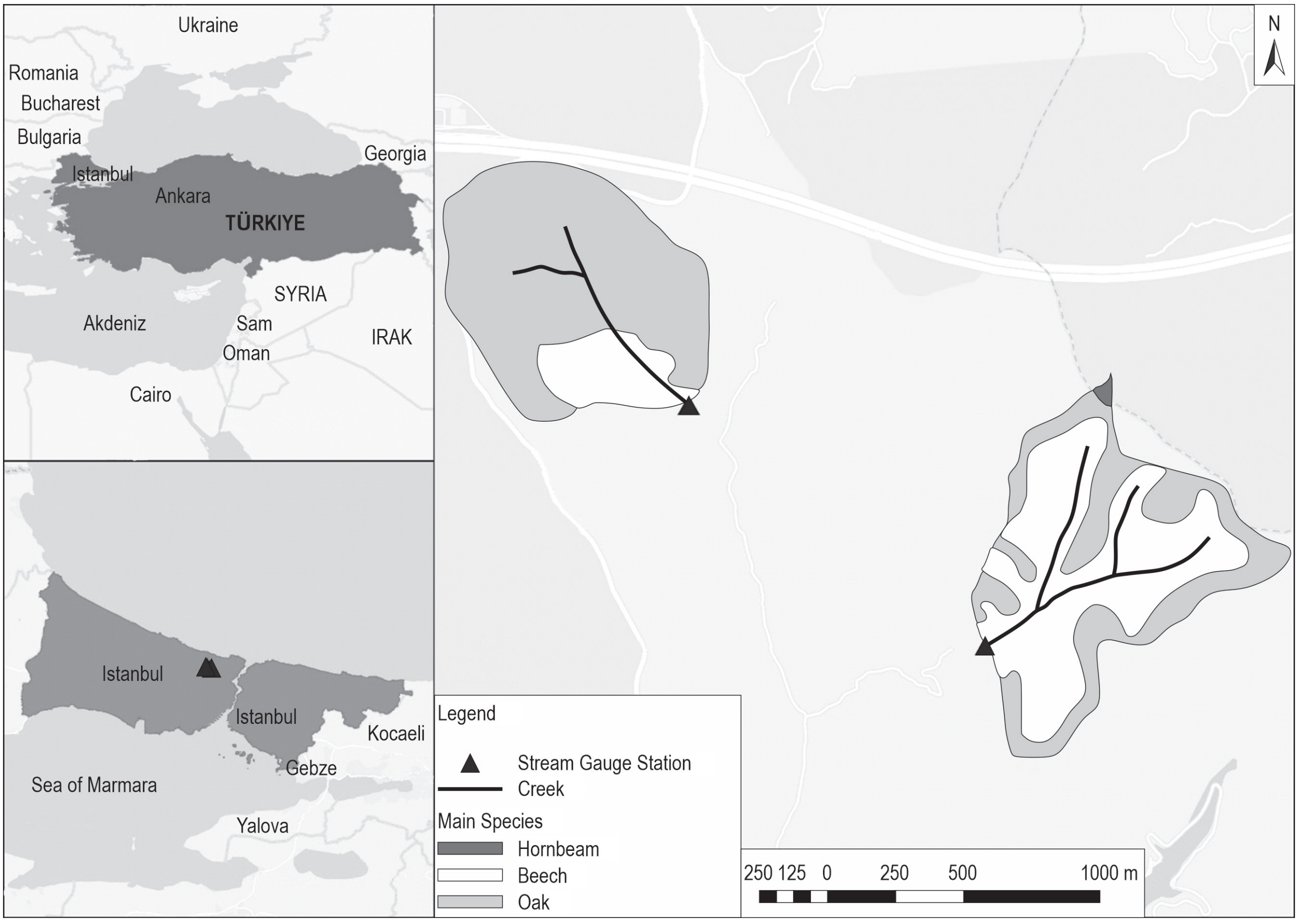

Fig. 1 Location of paired catchments

Serengil et al. 2007). In this well-established technique, the paired catchments are monitored for a few years during the calibration period before a treatment is applied. The precipitation and runoff are recorded and evaluated on a daily, monthly, or annual basis. Eq. (1) before the treatments that link streamflow of the control catchment to the streamflow of the treatment catchment is called calibration equation and is in the simple form as follows:

$$Q_t = a * Q_c + b \quad (1)$$

Where:

Q_t monthly flow of treatment catchment
Q_c monthly flow of control catchment
a, b linear regression coefficients.

The monitoring of the catchments continued during the treatment, and the years that followed in both control and treatment catchments. In our case, the calibration (pre-treatment) and treatment (post-treatment) periods were determined for four years each considering that the slight thinning treatments do not have long lasting hydrological impacts in these ecological conditions.

The difference between the observed and predicted flows reveals the impact of thinning. While calculating the difference, upper and lower bounds of prediction were also considered that are ±0.05 of the predicted values as shown in calibration graphs.

2.3 Carbon Modeling

The carbon modeling part of the study involved all six carbon pools including aboveground biomass (AGB), belowground biomass (BGB), deadwood (DW), litter (L), and harvested wood products (HWP) in line with IPCC (2006). A powerful software, the Carbon Budget Model (CBM–CFS3), was used to calculate and assess the responses of carbon pools to any management intervention or disturbance. The model uses the IPCC methods as a baseline combined with country-specific coefficients as necessary (Kurz et al. 2009). It requires detailed disturbance descriptions (rules) and forest growth models. The model calculations are

Table 1 Stand age and total stand volumes (m^3) for different growth models in one hectare

Age	NFI*	Korf	Michajlov	Chapman-Richards	Gompertz	Betalanffy
5	1.5	0	0.01	1.15	5.79	1.95
10	11.54	1.34	3.42	9.27	14.86	12.38
26	104.65	99.7	106.69	102.46	98.13	107.8
40	197.71	227.75	226.49	223.97	221.97	223.85
51	350	310.94	306.19	312.21	316.77	308.55
82	436.54	465.26	463.46	471.33	475.21	469.41
100	535	520.49	523.99	515.12	510.17	517.93
R^2 Values	1	0.9867	0.9863	0.986	0.9855	0.9858

*NFI – National Forest Inventory

based on IPCC gain-loss method (2006) for simulating forest carbon stock changes for different pools and between pools for past, present, and future. Also, it can incorporate different scenarios comparable with the current situation.

Pilli and Grassi (2021) tested the model in the EU region by also creating a EU-specific database (Pilli et al. 2016a, Pilli et al. 2016b). The climatic zones of the database have similarities in annual mean temperature, annual total precipitation and main tree species to Türkiye's ecozones and ecological conditions.

Several studies already described the detailed model structure (CBM–CFS3) including interactions between pools, disturbance and management matrices, and stock change computations (Kurz et al. 2009, Smyth et al. 2011, Stinson et al. 2011, Kurz et al. 2018, Pilli et al. 2017).

Local growth models (age-volume-based) and local climatic conditions (annual mean temperature) were used in this study. The EU-Archive Index Database was also used for some specific coefficients (Pilli et al. 2016b), which is nearly identical to our ecologic conditions. Based on our field measurements, age-volume relations were created by using Chapman-Richards growth model derived from the Bertalanffy function. It is currently the most utilized growth function worldwide (Table 1), and it provided similar results as our local yield tables. We also performed a model tune-up by using recent local studies on growth models of the species under consideration (Usta et al. 2019).

In our analysis, litter and deadwood pools were combined since the deadwood amount was considerably low. The research site is close to the recreational areas, and firewood collection by the visitors is widespread.

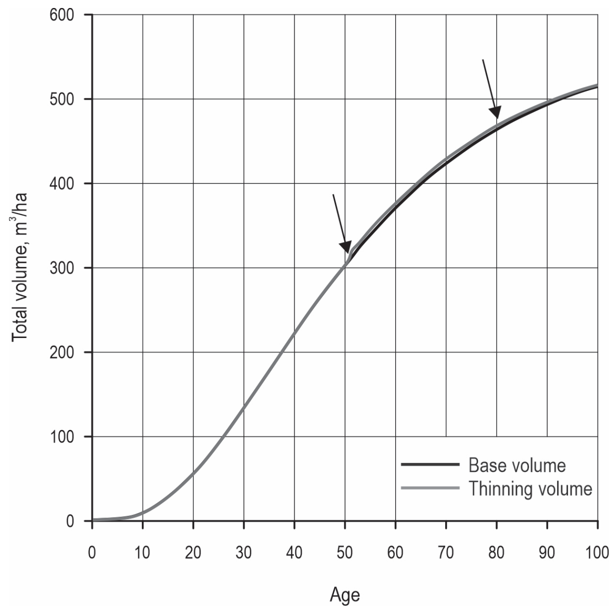

Fig. 2 Growth curve created for Mixed-Broadleaved forest stand in Istanbul, Türkiye

Standard 400 m^2 sample plots were used with an intensive grid scheme to calibrate the model with basic stand parameters (i.e., species composition, age, diameter at breast height, tree height). Deadwood, litter, and soil were sampled to analyze and calculate the C contents by laboratory analysis. In 2017, the stand age was 82, with an average tree diameter and height of 29.1±3.1 cm, and 16.6±3.4 m, respectively.

In 2007, the measured standing volume was 322.81 m^3 ha^{-1}, increasing to 436.54 m^3 ha^{-1} at the age of 82 in 2017 (Fig. 2).

The first thinning event (11%) was performed in 1986 when the average stand age was 51, while the second (18%) was in 2011.

2.4 Harvested Wood Products

The HWP pool with country-specific coefficients and EFs was calculated using First Order Decay Function (FODF) as IPCC (2006) suggested. The FODF (2) and the parameters we used were:

$$C(i+1) = e - k * C(i) + ((1 - e - k)/k) * Inflow\ (i) \quad (2)$$

Where:

i year

C(i) carbon stock in particular HWP category at the beginning of the year *i*, Gg C

k decay constant of FOD for each HWP category

k *ln*(2)/*HL*, where *HL* is half-life

Inflow(i) inflow to particular HWP category during the year

(i) Gg C. yr^{-1}.

The carbon stock change of the HWP category during the year (*i*) is calculated according Eq. (3):

$$\Delta C(i) = C(i+1) - C(i)'' \quad (3)$$

Half-life value for sawn wood is 35 years

Half-life value for wood panels is 25 years

Decay constant of FOD for sawn wood is 0.020

Decay constant of FOD for wood panels is 0.028.

3. Results

3.1 Hydrologic Impacts of Thinning

Calibration equations between the treatment and control catchments were established for the four-year pre-treatment before each thinning treatment (Fig. 3 and 4). The forest stands in both catchments remained unmanaged during the whole monitoring period except for the two thinnings. Both monthly calibration equations were quite good to perform the methodology. The coefficient of fit was slightly better for the second treatment.

We predicted the W–IV streamflow through the calibration equations and compared it with the observed flow for four years following the treatment (Fig. 5 and 6). After the first thinning (1986), a low flow period was observed until October. The observed flow increased quickly with the start of the autumn rains and stayed over the predicted flow until February 1987. The difference in the precited and observed monthly flows shrinked to zero in March and continued quite identical.

The second treatment (2011) corresponded to a high flow period of winter and early spring. Therefore, the response of the observed flow was stronger for the first six months following the treatment (Fig. 6).

A total water surplus of 113.05 mm was estimated for the post 4-year following the first treatment (Table 2).

The second thinning produced a total water yield surplus of 100.76 mm for the following 4-years.

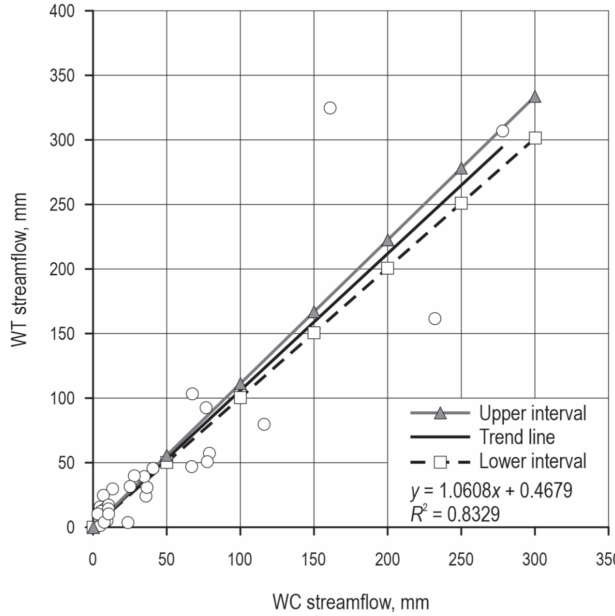

Fig. 3 Calibration graph and equation for the first treatment in 1986

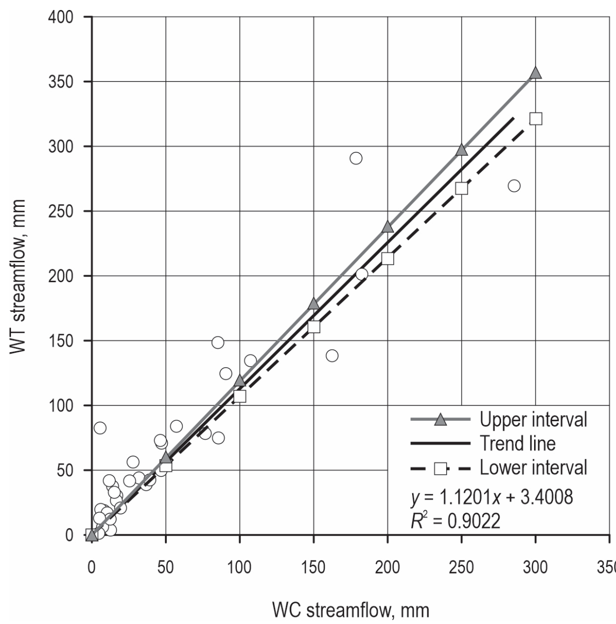

Fig. 4 Calibration graph and equation for the second treatment in 2011

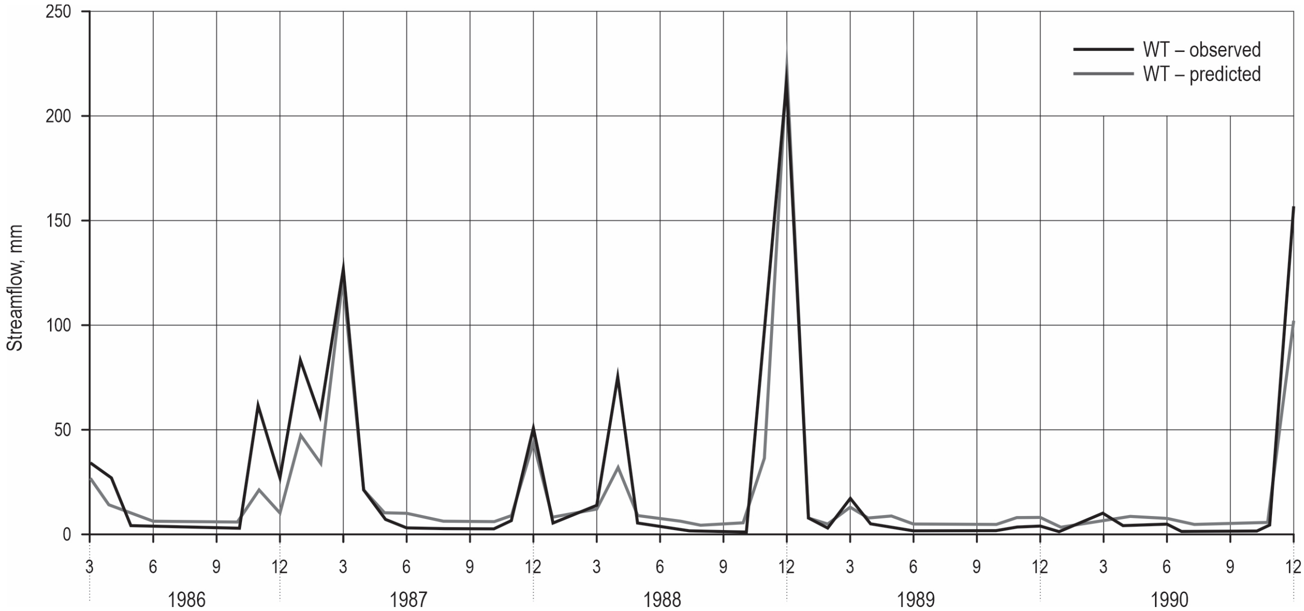

Fig. 5 Comparison of observed and predicted streamflow data during the post-treatment period (1986–1990)

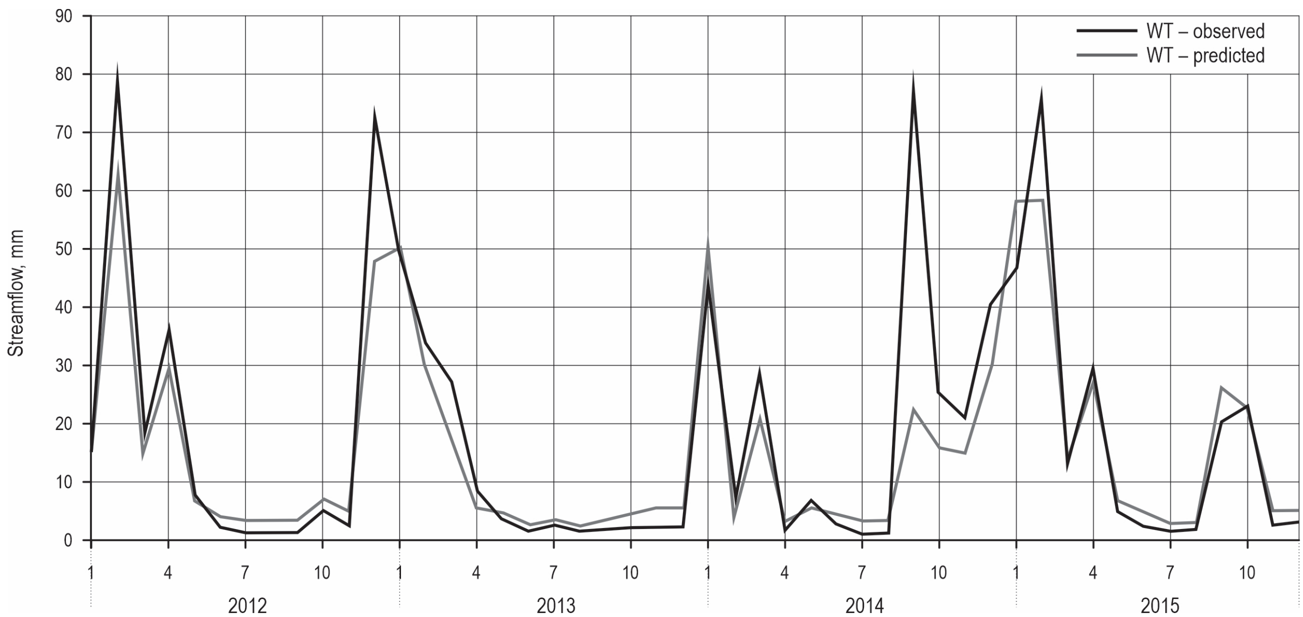

Fig. 6 Comparison of observed and predicted streamflow data during the post-treatment period (2012–2015)

Therefore, the thinnings roughly caused an increased water yield of around 100 mm in 4 years after the treatment (Table 2), corresponding to an annual average of around 25 mm.

3.2 Thinning Impacts on Carbon Stocks

The thinning treatments resulted in the removal of standing stock, which significantly affected the biomass carbon stocks. However, the impacts on dead wood, litter, and soils were less dramatic. The treatments also created HWP as the sixth carbon pool. Each cutting treatment caused a certain amount of timber to move from the aboveground biomass carbon pool to the HWP pool to start oxidizing theoretically through first-order decay function (FODF) (Fig. 7, 8, and 9). The belowground biomass left on the site had a slow conversion to the soil carbon pool with a long decay duration based on the algorithm in the CBM model.

Table 2 Difference between observed and predicted flows for various post-treatment periods

Thinning	Observed – Predicted Flows (mm) in the Post Treatment period				
Year (Intensity)	3 Months	6 Months	12 Months	24 Months	48 Months
1986 (11%)	12.33	1.30	105.38	80.12	113.05
2011 (18%)	16.48	20.05	32.87	31.92	100.76

As explained above, the selective thinning treatments usually increase the mean annual increment of the remaining individuals due to increased soil water and nutrient availability. However, in our case, the increment was inefficient in triggering growth due to low post-treatment precipitation, especially after the second treatment (Fig. 7). In the first treatment, the remaining trees grew faster during the early 2–3 years but later became similar to the stands in the Control Watershed.

The thinnings enhanced the litter carbon pool since slash composed of leaves and branches were left on site. The deadwood and litter carbon stock increased to around 3.5 from 2.5 tons per hectares after the first treatment and slightly dropped to a carbon stock level of 3.1 tons per hectare during the following years (Fig. 8). The influence of increase and decrease in litter carbon stock was not significant enough to affect soil carbon stock according to CBM model simulations. After the first and second thinning treatment, the litter carbon stocks decreased by around 0.1 and 0.5 tons per hectare per year. In the second case, a 0.1 ha per year increase was calculated in soil carbon stock by CBM, while there was no change after the first treatment (Fig. 8).

The treatments caused a decrease in litter and deadwood carbon stocks compared to control stands by the end of the assessment period. The forest stands in the catchments had almost the same litter carbon stocks in 1980, but in 2021, the control catchment forests had 4.6, while treatment catchment had 3.0 tons per hectares of carbon in this pool. The CBM model applies around ten years of enhanced mineralization in litter and deadwood carbon stocks after the thinning treatments, for this ecologic environment.

Soil carbon stocks were much less responsive to the treatments. As explained above, a slight increase occurred (W–IV) after the second treatment (Fig. 9) as harvest residues were added.

The harvests added 1520 m^3 and 3867 m^3 of wood to the HWP pool in 1986 and 2011, respectively. The pool discharged slowly in time with emissions calculated through the first-order decay function as explained above. Considering that the harvested product was industrial roundwood, the calculated HWP pool discharge was to end beyond 2100 (Fig. 10). The carbon added to the HWP pool was 8 tons per hectare for the first treatment in 1986 and slightly over 20 tones after the second thinning. These amounts have all been received from the AGB pool.

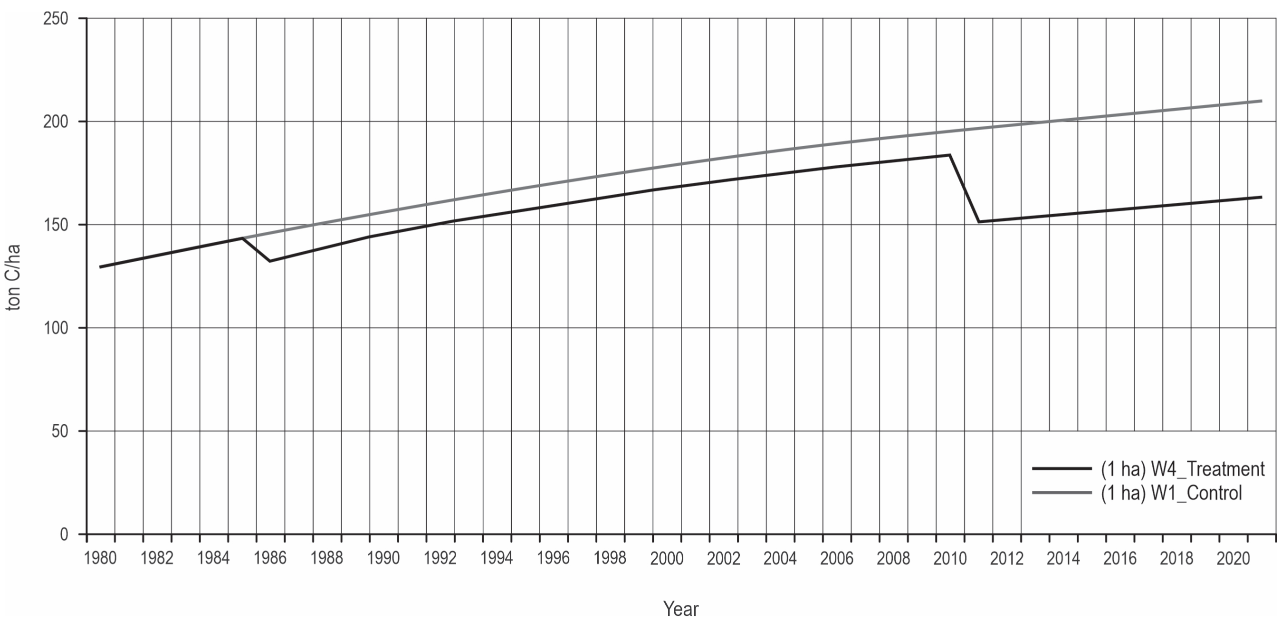

Fig. 7 Change in total biomass carbon stocks during the assessment period

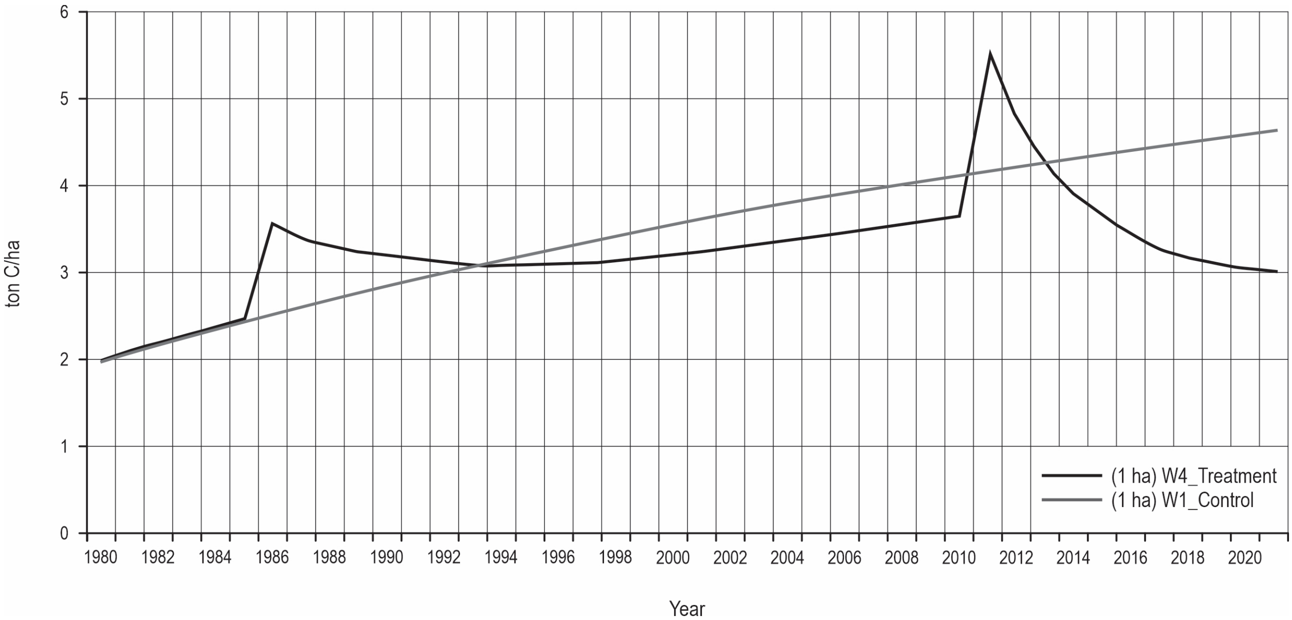

Fig. 8 Changes in litter and deadwood carbon stocks of forest stands during the assessment period

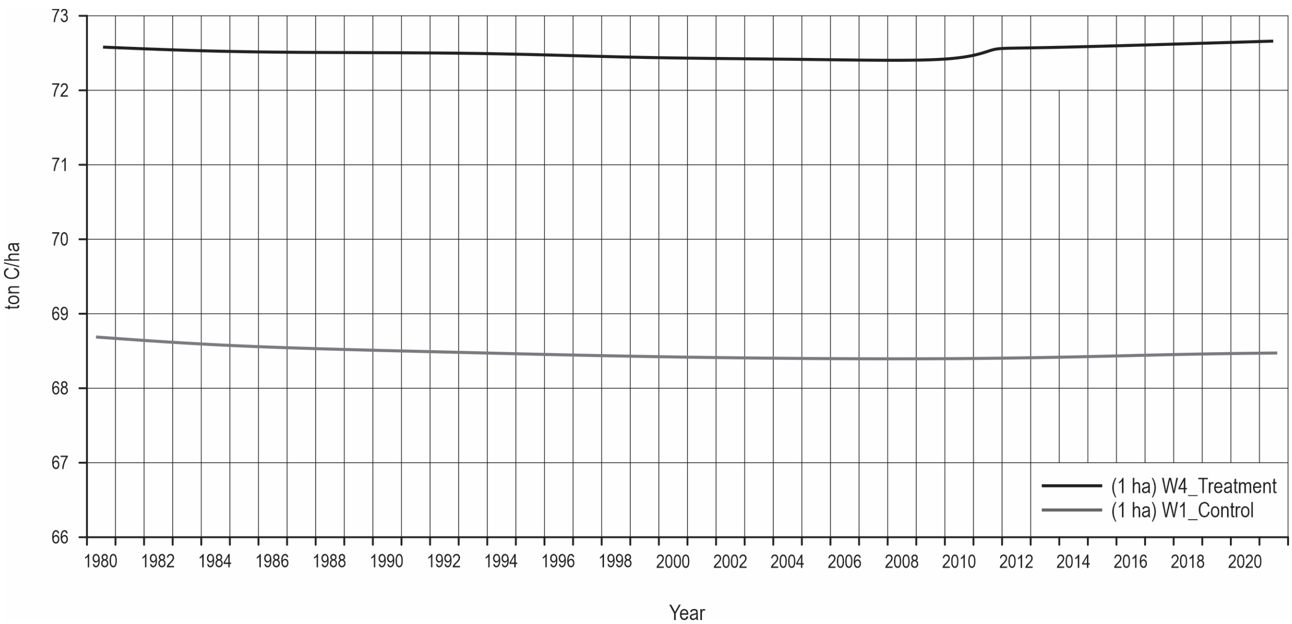

Fig. 9 Changes in soil organic carbon during the assessment period

The Net Primary Productivity (NPP) enables us to understand the effectiveness of the treatment on total biomass carbon stocks. The NPP increased slightly after the first treatment as thinning caused a decrease in the stand closure to lessen the competition between the remaining individuals (Fig. 11). However, the stimulated increase did not last long. The NPP of the thinned stands dropped below the control stands level after 1991, and the difference in NPP remained stable until the second treatment. The second thinning caused a similar but more drastic change in NPP compared to the first one.

As seen in Fig. 12, the carbon stock difference between the treatment and control catchments was 3.9 tons C/ha at the very beginning of the assessment based on the measured soil carbon stocks. With the

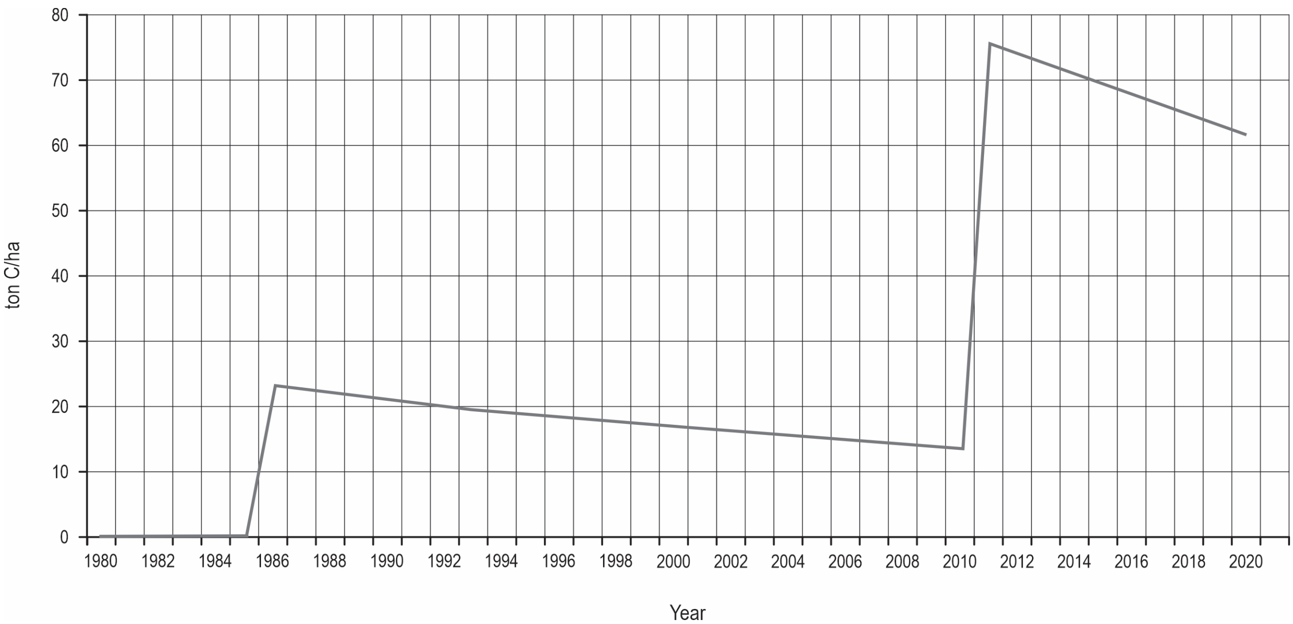

Fig. 10 Changes in HWP carbon pool during the assessment period

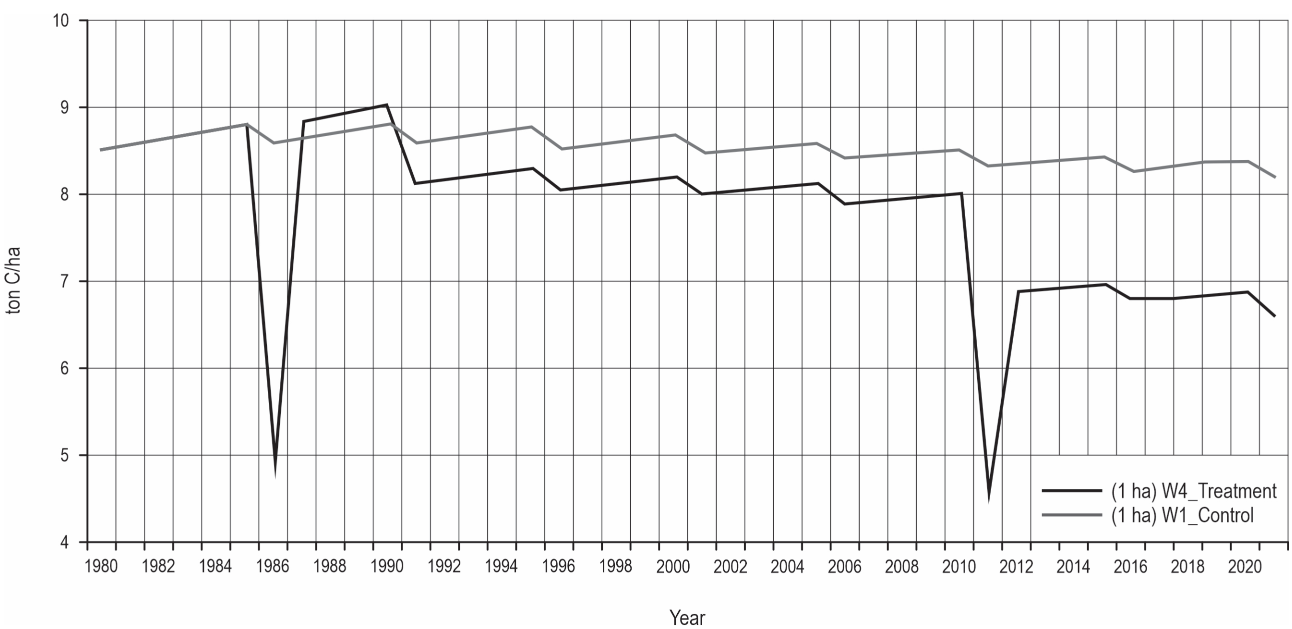

Fig. 11 Changes in Net primary productivity during the assessment period

first thinning treatment, the total carbon stocks of the treated stands dropped due to the loss in annual increment, relocation of cut timber to the HWP pool, and some oxidation calculated during the harvest. The treatment equalized the C stocks per hectare of the treatment and catchments. However, there was around a 1 ton C/ha increase in litter carbon stocks with the slash left on site (Fig. 12).

During the years following the first treatment, the difference of increment between treated and control catchments balanced, while the difference in litter carbon stock also disappeared. However, emissions from HWP continued. Carbon stocks per hectare for the catchments leveled in 1995, and treatment catchment carbon stocks continued decreasing with emissions from the HWP pool.

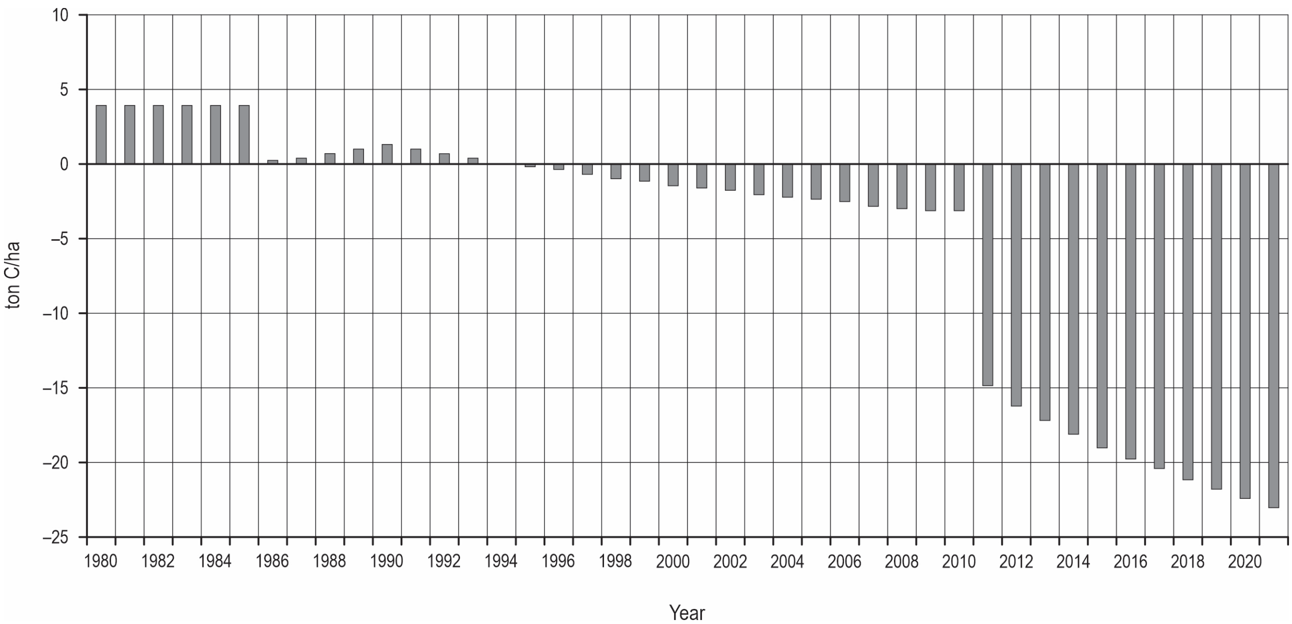

Fig. 12 Total C stocks in 6 C pools in W–IV during the assessment period

A similar change in carbon stocks occurred in the second thinning treatment, but the influence was more effective this time. By the end of the assessment period, the total change in the carbon stocks of the treated stands was 27 tons C per hectare compared to control stands.

4. Discussion

Two thinning treatments were analyzed by using paired catchment methodology and a well-proven carbon model. The hydrologic response was slightly increased streamflow in line with the relevant thinning literature (Sun et al. 2015, Komatsu et al. 2010). The water yield increase for the first treatment was 105.38 mm for the first year and 113.05 mm for four years after the treatment. The streamflow increase was similar for the second thinning treatment (+18%), reaching 100.76 mm for four years after the treatment. Considering that the region annual precipitation is around 1200 mm and the runoff coefficient of the catchments are between 20–25% (Serengil et al. 2007), the water surplus accounted for about 10 percent annually during the post 4-year periods following the treatments. The water surplus did not occur during the following dry summer months but during rainy winter months of the same year. The forested catchments are known to have more extensive subsurface flow components compared to developed ones. Therefore, it is presumed that the subsurface components need to be charged before a change in streamflow could be observed.

Furthermore, the heavy rains end up by April in the region and the light summer rains have a meager influence on the streamflow because most events do not even fill up the interception capacities of the stands. The same pattern went on for the following years. Therefore, the treatments seemed to increase the water yield only during the rainy season, that is in the winter.

These increased streamflow rates are comparable or slightly higher than other thinning studies reported (Bosch and Hewlet 1982, Reinhart et al. 1963, Harr et al. 1979, Dung et al. 2012). Some studies even reported a stronger influence. According to Lane and Mackay (2001), there has been a significant 31 percent increase in streamflow during the first 4 years following a 12% thinning treatment. Yang et al. (2019) reported thinning treatments that affected runoff for 12 years and estimated a 263 mm yr^{-1} increase in the annual runoff.

The effects of thinnings on carbon stocks were more visible. The total C stocks of the forests in the treatment catchment were higher than the control at the beginning of the assessment period, and started to decrease continuously following the first and second treatment, reaching a difference of 27 tons per ha by 2020. The second treatment had more substantial impacts on C pools than the first due to more timber harvested.

The selective thinning treatments are expected to increase the increment of the remaining individuals due to reduced competition among the individuals

(Navarro-Cerrillo et al. 2023). However, in our case, the increment did not trigger the growth due to low post-treatment precipitation, especially after the second treatment. In the first treatment, the remaining trees grew faster during the early 2–3 years but later became identical with the stands in the Control Watershed (Shi et al. 2023, Yang et al. 2022).

In the early years, the harvests also caused increases in litter and deadwood carbon stocks, but these pools gradually depleted due to enhanced mineralization reaching an equilibrium state. The difference in litter carbon stocks of treated and control stands was 0.5 tons per hectare before the second thinning treatment. Like the first one, the second treatment caused a quick replenishment in litter carbon stocks and a follow-up depletion with enhanced mineralization caused by additional light and moisture (Kern et al. 2021b, Wang et al. 2018, Jandl et al. 2007, Kunhamu et al. 2009).

The influence of increased litter and deadwood on soil carbon stocks was detectable but minimal. In both treatments, the soil carbon stocks rose very slightly. The increase in soil carbon stocks was more apparent and long-lasting in the second treatment. In a study by Kim (2015), thinning treatment increased the soil carbon concentrations at the depth of 0–30 cm in the first four months after the thinning event, but there was no significant change after four months. However, some studies mentioned considerable impacts on soil nutrient pools and soil physical properties (i.e. Johnson and Curtis 2001).

As explained above, the thinning initiated an HWP pool with the timber produced. The process was an instant biomass carbon move to the HWP pool, where it was emitted continuously based on the half-lives of the products. We did not track the harvested timber but assumed that it was used in producing wood panels and sawn wood based on the information provided by the forestry enterprise. The established HWP pool maximized in the harvest year and then started decreasing based on the first-order decay function, such as emissions. However, the HWP emissions go on for a very long time compared to other pools since the products have long half-lives (Paluš et al. 2020). According to Profft (2009), the relation between harvest and wood products is vital for the net carbon balance in the forest sector. Raymer (2011) mentioned many benefits of using harvested wood products in different sectors. Iordan (2018) also reported a negative emission effect of harvested wood products in Norway, Sweden, and Finland.

Consequently, the results indicated significant changes in carbon stocks and water budgets. The hydrological impacts were in line with several other studies reported, but C stock changes were slightly controversial. As given above, most studies mentioned enhanced growth of the remaining stands after thinning. In our case, it was also detected to some extent, but it was weak to compensate for the removed wood. The climatic conditions, species composition, stand structure, soils, and thinning rate are the factors that determine the recovery of the stands (Saunders et al. 2012). The age of the stands and site conditions might have suppressed the growth in our case.

5. Conclusions

In this study, the hydrological and carbon related impacts of two slight thinning treatments were analyzed. The thinning treatments that caused the removal of 11 and 18 percent of the basal area increased the water yield from the experimental catchment covered with old-growth deciduous forest ecosystems. The increases in the following 4 years were very similar and around 25 mm per year, corresponding to 10–15 percent of the annual water yield. The treatments also caused a significant loss of carbon that takes decades to recover. The total ecosystem biomass C stock of the forest stands in the control catchment is estimated to reach almost 210 tons by 2020, while the stock of thinned stands remained slightly over 160 tons per hectare. When a minor difference in litter and deadwood carbon stocks was added, the difference in total carbon stocks reached over 50 tons per hectare. That is significant for carbon budgets of any forest type and shows the trade-off between ecosystem water production and carbon removals. As explained above, we consider that the carbon stocks could recover if the treatments were performed in early stand ages due to higher increment ability.

Consequently, our null hypothesis was declined, since there was a detectable increase in water yield during the following four years of slight thinning treatments, and since the reduction in aboveground carbon stocks continued for more than three decades.

The results are important for the management of deciduous forests concerning climate-related ecosystem services since the response of the forest stands in terms of water and carbon have been analyzed in detail. Thinning treatments are very common, but it is hard to determine the hydrologic impacts of such slight treatments due to climatic variability. The paired catchment methodology enabled it. The water production perspective indicated a more debatable and short-lasting impact, strongly affected by the seasonality of precipitation, ET, and other climatic parameters. It was concluded that the timing of the treatment and accompanying climate conditions have a strong influence on the impact level. On the other hand, the carbon perspective represented a more drastic, precise, and long-lasting impact.

Acknowledgments

This study uses field measurement data collected in the framework of a long-term ecological research initiated in 1978 by Nihat Balcı, Necdet Özyuvacı, Süleyman Özhan, Ahmet Hızal, and Kamil Şengönül. The recent field measurements used in the assessments are from Ufuk Özkan's Ph.D. field studies.

Availability of Data and Materials

The datasets used during the current study are available from the corresponding authors on reasonable request.

Code Availability

CBM–CFS3 and EU Archive Index Database are open source and free to access.

6. References

Andrade, E.M., Guerreiro, M.J.S, Palácio, H.A.Q, Campos, D.A., 2020: Ecohydrology in a Brazilian tropical dry forest: thinned vegetation impact on hydrological functions and ecosystem services. Journal of Hydrology: Regional Studies 27: 100–649. https://doi.org/10.1016/j.ejrh.2019.100649

Balcı, A.N., Ozyuvacı, N., Ozhan, S., 1986: Sediment and nutrient discharge through streamflow from two experimental watersheds in natural oak-beech forest ecosystems near Istanbul, Turkey. Journal of Hydrology 85(1–2): 31–47. https://doi.org/10.1016/0022-1694(86)90075-2

Balcı, A.N., Ozyuvacı, N., Ozhan, S., Sengonul, K., 1993: Calibration of paired experimental watersheds with respect to streamflow characteristics in mature oak beech forest ecosystem near Istanbul-Turkey. Revue de la Faculté des Sciences de l'Université d'Istanbul A 43a: 13–32.

Bosch, J.M., Hewlett, J.D., 1982: A review of catchment experiments to determine the effect of vegetation change on water yield and evapotranspiration. Journal of Hydrology 55 (1–4): 3–23. https://doi.org/10.1016/0022-1694(82)90117-2

Dung, B.X., Gomi, T., Miyata, S., Sidle, R.C., Kosugi, K., Onda, Y., 2012: Runoff responses to forest thinning at plot and catchment scales in a headwater catchment draining Japanese cypress forest. Journal of Hydrology 444–445: 51–62. https://doi.org/10.1016/j.jhydrol.2012.03.040

Gökbulak, F., Şengönül, K., Serengil, Y., Özhan, S., Yurtseven, I., Uygur, B., Özçelik, M.S., 2016: Effect of Forest Thinning on Water Yield in a Sub-Humid Mediterranean Oak-Beech Mixed Forested Watershed. Water Resources Management 30(14): 5039–5049. https://doi.org/10.1007/s11269-016-1467-7

Gong, C., Tan, Q., Liu, G., Xu, M., 2021: Forest thinning increases soil carbon stocks in China. Forest Ecology and Management 482: 118–812. https://doi.org/10.1016/j.foreco.2020.118812

Harr, R.D., Fredriksen, R.L., Rothacher, J., 1979: Changes in streamflow following timber harvest in Southwest Oregon. Research Paper PNW-RP-249. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 22 p.

Iordan, C.M., Hu, X., Arvesen, A., Kauppi, P., Cherubini, F., 2018: Contribution of forest wood products to negative emissions: historical comparative analysis from 1960 to 2015 in Norway, Sweden and Finland. Carbon Balance and Management 13(1): 1–16. https://doi.org/10.1186/s13021-018-0101-9

IPCC, 2006: IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K. (eds). Published: IGES, Japan.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007: How strongly can forest management influence soil carbon sequestration? Geoderma 137(3–4): 253–268. https://doi.org/10.1016/j.geoderma.2006.09.003

Johnson, D.W., Curtis, P.S., 2001: Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management 140(2–3): 227–238. https://doi.org/10.1016/s0378-1127(00)00282-6

Kern, C.C., Kenefic, L.S., Kuehne, C., Weiskittel, A.R., Kaschmitter, S.J., D'Amato, A.W., Dey, D.C., Kabrick, J.M., Palik, B.J., Schuler, T.M., 2021: Relative influence of stand and site factors on aboveground live-tree carbon sequestration and mortality in managed and unmanaged forests. Forest Ecology and Management 493: 119266. https://doi.org/10.1016/j.foreco.2021.119266

Kim, S., Yoon, T.K., Han, S., Han, S.H., Lee, J., Kim, C., Lee, S.T., Seo, K.W., Yang, A.R., Son, Y., 2015: Initial effects of thinning on soil carbon storage and base cations in a naturally regenerated *Quercus* spp. forest in Hongcheon, Korea. Forest Science and Technology 11(3): 172–176. https://doi.org/10.1080/21580103.2014.957357

Kunhamu, T., Kumar, B., Viswanath, S., 2009: Does thinning affect litterfall, litter decomposition, and associated nutrient release in Acacia mangium stands of Kerala in peninsular India? Canadian Journal of Forest Research 39(4): 792–801. https://doi.org/10.1139/x09-008

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., Apps, M.J., 2009: CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecological Modelling 220(4): 480–504. https://doi.org/10.1016/j.ecolmodel.2008.10.018

Kurz, W.A., Hayne, S., Fellows, M., MacDonald, J., Metsaranta, J., Hafer, M., Blain, D., 2018: Quantifying the impacts of human activities on reported greenhouse gas emissions and removals in Canada's managed forest: conceptual framework and implementation. Canadian Journal of Forest Research 48(10): 1227–1240. https://doi.org/10.1139/cjfr-2018-0176

Lane, P.N., Mackay, S.M., 2001: Streamflow response of mixed-species eucalypt forests to patch cutting and thinning treatments. Forest Ecology and Management 143(1–3): 131–142. https://doi.org/10.1016/S0378-1127(00)00512-0

McDowell, N.G., Adams, H.D., Bailey, J.D., Hess, M., Kolb, T.E., 2006b: Homeostatic Maintenance of Ponderosa Pine Gas Exchange In Response To Stand Density Changes. Ecological Applications 16(3): 1164–1182. https://doi.org/10.1890/1051-0761

Moreau, G., Auty, D., Pothier, D., Shi, J., Lu, J., Achim, A., Xiang, W., 2020: Long-term tree and stand growth dynamics after thinning of various intensities in a temperate mixed forest. Forest Ecology and Management 473: 118311. https://doi.org/10.1016/j.foreco.2020.118311

Moreno-Gutiérrez, C., Barberá, G.G., Nicolás, E., de Luis, M., Castillo, V.M., Martínez-Fernández, F., Querejeta, J.I., 2011: Leaf δ 18O of remaining trees is affected by thinning intensity in a semiarid pine forest. Plant, Cell & Environment 34(6): 1009–1019. https://doi.org/10.1111/j.1365-3040.2011.02300.x

Navarro-Cerrillo, R., Cachinero-Vivar, A.M., Pérez-Priego, Ó., Cantón, R.A., Beguerí, A.S., Camarero, J.J., 2023: Developing alternatives to adaptive silviculture: Thinning and tree growth resistance to drought in a Pinus species on an elevated gradient in Southern Spain. Forest Ecology and Management 537: 120936. https://doi.org/10.1016/j.foreco.2023.120936

Özhan, S., 1977: Variation in Some Hydrologic Properties of Forest Floor as Related to Certain Environmental Factors in Ortadere Watershed of Belgrad Forest. Publication of Istanbul University, Faculty of Forestry Publication, 235; 179 p.

Özhan, S., Gökbulak, F., Serengil, Y., Özcan, M., 2010: Evapotranspiration from a mixed deciduous forest ecosystem. Water Resources Management 24: 2353–2363. https://doi.org/10.1007/s11269-009-9555-6

Paluš, H., Parobek, J., Moravčík, M., Kovalčík, M., Dzian, M., Murgaš, V., 2020: Projecting Climate Change Potential of Harvested Wood Products under Different Scenarios of Wood Production and Utilization: Study of Slovakia. Sustainability 12(6): 2510. https://doi.org/10.3390/su12062510

Pilli, R., Grassi, G., Kurz, W.A., Fiorese, G., Cescatti, A., 2017: The European forest sector: past and future carbon budget and fluxes under different management scenarios. Biogeoscience 14(9): 2387–2405. https://doi.org/10.5194/bg-14-2387-2017

Pilli, R., Grassi, G., 2021: Provision of technical and scientific support to DG ESTAT in relation to EU land footprint estimates and gap-filling techniques for European forest accounts (LAFO). EUR 30581 EN, Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/73306

Pilli, R., Grassi, G., Kurz, W.A., Viñas, R.A., Guerrero, N., 2016a: Modelling forest carbon stock changes as affected by harvest and natural disturbances. I. Comparison with countries' estimates for forest management. Carbon Balance and Management 11: article number 5. https://doi.org/10.1186/s13021-016-0047-8

Pilli, R., Grassi, G., Kurz, W.A., Moris, J.V., Viñas, R.A., 2016b: Modelling forest carbon stock changes as affected by harvest and natural disturbances. II. EU-level analysis. Carbon Balance and Management 11: article number 20. https://doi.org/10.1186/s13021-016-0059-4

Profft, I., Mund, M., Weber, G.E., Weller, E., Schulze, E.D., 2009: Forest management and carbon sequestration in wood products. European Journal of Forest Research 128(4): 399–413. https://doi.org/10.1007/s10342-009-0283-5

Raymer, A., Gobakken, T., Solberg, B., 2011: Optimal forest management with carbon benefits included. Silva Fennica 45(3): 109. https://doi.org/10.14214/sf.109

Saunders, M., Tobin, B., Black, K., Gioria, M., Nieuwenhuis, M., Osborne, B., 2012: Thinning effects on the net ecosystem carbon exchange of a Sitka spruce forest are temperature-dependent. Agricultural and Forest Meteorology 157: 1–10. https://doi.org/10.1016/j.agrformet.2012.01.008

Serengil, Y., 2018: Climate Change and Carbon Management. Organizational Development Program, Ankara.

Serengil, Y., Gökbulak, F., Özhan, S., Hızal, A., Şengönül, K., Balcı, A.N., Özyuvacı, N., 2007: Hydrological impacts of a slight thinning treatment in a deciduous forest ecosystem in Turkey. Journal of Hydrology 333 (2–4): 569–577. http://dx.doi.org/10.1016/j.jhydrol.2006.10.017

Shi, J., Xu, F., Xiang, W., 2023: Fusing tree-ring and permanent sample plot data to model influences of climate and thinning on tree growth in larch plantations in northeast China. Forest Ecology and Management 531: 120800. https://doi.org/10.1016/j.foreco.2023.120800

Smyth, C.E., Kurz, W.A., Trofymow, J.A., 2011: Including the effects of water stress on decomposition in the Carbon Budget Model of the Canadian Forest Sector CBM-CFS3. Ecological Modelling 222(5): 1080–1091. https://doi.org/10.1016/j.ecolmodel.2010.12.005

Sohn, J.A., Gebhardt, T., Ammer, C., Bauhus, J., Häberle, K.H., Matyssek, R., Grams, T.E., 2013: Mitigation of drought by thinning: Short-term and long-term effects on growth and physiological performance of Norway spruce (*Picea abies*). Forest Ecology and Management 308: 188–197. https://doi.org/10.1016/j.foreco.2013.07.048

Sun, W., Ishidaira, H., Bastola, S., Yu, J., 2015: Estimating daily time series of streamflow using hydrological model calibrated based on satellite observations of river water surface width: Toward real world applications. Environmental Research 139: 36–45. https://doi.org/10.1016/j.envres.2015.01.002

Stinson, G., Kurz, W.A., Smyth, C.E., Neilson, E.T., Dymond, C.C., Metsaranta, J.M., Boisvenue, C., Rampley, G.J., Li, Q., White, T.M., Blain, D., 2011: An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. Global Change Biology 17(6): 2227–2244. https://doi.org/10.1111/j.1365-2486.2010.02369.x

Tsamir, M., Gottlieb, S., Preisler, Y., Rotenberg, E., Tatarinov, F., Yakir, D., Tague, C., Klein, T., 2019: Stand density effects on carbon and water fluxes in a semi-arid forest, from leaf to stand-scale. Forest Ecology and Management 453: 117573. https://doi.org/10.1016/j.foreco.2019.117573

Usta, A., Yilmaz, M., Yilmaz, S., Kocamanoglu, Y.O., Genc, E., Turna, I., 2019: The effects of thinning intensity on the growth of oriental beech (*Fagus orientalis* Lipsky) plantations in Trabzon, NE Turkey. Šumarski list 143(5–6): 231–240. https://doi.org/10.31298/sl.143.5-6.4

Van Deusen, P., 2010: Carbon sequestration potential of forest land: Management for products and bioenergy versus preservation. Biomass and Bioenergy 34(12): 1687–1694. https://doi.org/10.1016/j.biombioe.2010.03.007

Wang, W., Page-Dumroese, D., Jurgensen, M., Tirocke, J., Liu, Y., 2018: Effect of forest thinning and wood quality on the short-term wood decomposition rate in a Pinus tabuliformis plantation. Journal of Plant Research 131(6): 897–905. https://doi.org/10.1007/s10265-018-1069-y

Yang, H., Choi, H.T., Lim H., 2019: Effects of Forest Thinning on the Long-Term Runoff Changes of Coniferous Forest Plantation. Water 11(11): 2301. https://doi.org/10.3390/w11112301

Yang, L., Qin, J., Geng, Y., Zhang, C., Pan, J., Niu, S., Tian, D., Zhao, X., Wang, J., 2022: Long-term effects of forest thinning on soil respiration and its components in a pine plantation. Forest Ecology and Management 513: 120189. https://doi.org/10.1016/j.foreco.2022.120189

Yurtseven, I., Serengil, Y., Gökbulak, F., Şengönül, K., Ozhan, S., Kılıç, U., Uygur, B., Ozçelik, M.S., 2018: Results of a paired catchment analysis of forest thinning in Turkey in relation to forest management options. Science of The Total Environment 618: 785–792. https://doi.org/10.1016/j.scitotenv.2017.08.190

Zhou, T., Wang, C., Zhou, Z., 2020: Impacts of forest thinning on soil microbial community structure and extracellular enzyme activities: A global meta-analysis. Soil Biology and Biochemistry 149: 107915. https://doi.org/10.1016/j.soilbio.2020.107915

Authors' addresses:

Asisst. prof. Ufuk Özkan *
e-mail: ufuk.ozkan@ikc.edu.tr
Izmir Katip Celebi University
Faculty of Forestry
Department of Watershed Management
Çiğli-35620, İzmir
TÜRKİYE

Prof. Yusuf Serengil
e-mail: serengil@iuc.edu.tr
Prof. Ferhat Gökbulak
e-mail: fgokbulak@iuc.edu.tr
Asocc. prof. İbrahim Yurtseven
e-mail: ibrahimy@iuc.edu.tr
Asocc. prof. Betül Uygur Erdoğan
e-mail: uygurb@iuc.edu.tr
Reyhan Sağlam, MSc
e-mail: reyhan.demir@iuc.edu.tr
Istanbul University-Cerrahpasa
Faculty of Forestry
Department of Watershed Management
Bahçeköy-34320, Istanbul
TÜRKİYE

Erda Çeler, PhD
e-mail: erdaceler@ogm.gov.tr
General Directorate of Forestry
Department of Foreign Relations
Training & Research
Beştepe- 6560, Ankara
TÜRKİYE

* Corresponding author

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